TTC Distribution

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Abstract

A multichannel optical distribution system has been developed for the transmission of timing, trigger and control (TTC) signals to the front-end electronics controllers of LHC detectors from a single location in the vicinity of the central trigger processor. The signals can be broadcast to several thousand destinations from a relatively high power laser over an entirely passive optical fibre network with uncontrolled path lengths.

The system delivers the LHC timing reference and first-level trigger decisions with the corresponding bunch and event numbers, compensated for particle flight times and detector, electronics and propagation delays. In addition it provides for the simultaneous transmission of synchronized broadcast commands and individually-addressed controls and parameters, such as channel masks and calibration data.

I. INTRODUCTION

All the subdetectors of the proposed LHC experiments require quite extensive distribution systems for the transmission of timing, trigger and control signals to large numbers of front-end electronics controllers. A common solution to this TTC system requirement is expected to result in important economies of scale and permit a rationalization of the development, operational and support efforts required.

In conjunction with RD27, LHCC/LERB Project RD12 has developed a multi-function optoelectronic TTC distribution system [1] which can meet the requirements of the different subdetectors of the experiments. It has been adopted for the ATLAS [2] and CMS [3] TTC system backbones and is currently being considered for ALICE and LHC-B.

In each experiment the TTC system must control the detector synchronization and deliver to the front-end electronics controllers the necessary fast signals and messages that are phased with the LHC clock, orbit or bunch structure. These include the 40.08 MHz bunch-crossing clock, level-1 trigger decisions, bunch and event numbers, as well as test signals and broadcast commands.

The system incorporates programmable coarse and fine deskew facilities to compensate for different particle flight times and detector, electronics, propagation and test generator delays. It also transmits asynchronous slow controls and data such as individually-addressed channel enables and calibration parameters to several thousand destinations.

II. ARCHITECTURE

To minimise the level-1 trigger latency, the trigger processors and central trigger logic will be located in the underground control areas as close as possible to the cable labyrinths communicating with the detector caverns. A small number of relatively high-power laser sources will be installed at these locations to distribute the signals to their destinations through entirely passive all-glass networks composed of a hierarchy of optical tree couplers (see Fig. 1).

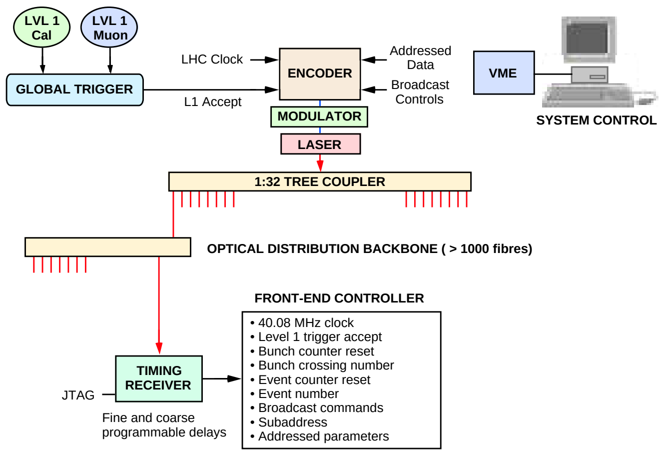

Fig. 1 TTC distribution components

The tree architecture of this distribution network is well matched to the physical configuration of the underground areas, the co-located signal sources and the dispersed destinations. It requires considerably less optical fibre than a star configuration of point-to-point links from a central fanout and permits the flexibility of extensive intermediate connectorization, since only the final destination connectors contribute significantly to the cost. The optical couplers have small size, low mass and unlimited bandwidth. They require no operating power and are potentially highly reliable.

Each laser transmitter serves a TTC distribution zone which is typically associated with a major component of a subdetector, such as an entire end-cap or barrel section. Owing to the small number of laser sources employed for the complete system, it is economically feasible to optimise performance and reliability by equipping all of them with full three-term feedback controllers providing precision temperature regulation and incorporating comprehensive low-noise stabilisation and protection circuitry.

Furthermore, continued improvements in the efficiency, reliability, intensity noise, spectral and modulation characteristics of laser diodes are to be expected during the many years preceding start-up of the LHC. As new devices become available, the architecture adopted allows the TTC system to be upgraded much more readily than if thousands of individual LED sources had been employed.

III. LASER TRANSMITTER

Several considerations have led to the selection of 1310 nm as the operating wavelength for the TTC systems. At this

Presented at the LERB Workshop on Electronics for LHC Experiments, Lisbon, 11-15 September 1995

wavelength the chromatic dispersion of normal optical fibre is negligible, so that Fabry-Perot laser diodes operating in multiple longitudinal modes can be used and the effect of the chirping caused by direct modulation is minimised. The overall length of fibre in each distribution path being only about 100 m, fibre attenuation is negligible. Hence in a short-range timing distribution system the minimum-dispersion wavelength of 1310 nm is more appropriate than the minimum-attenuation wavelength of 1550 nm.

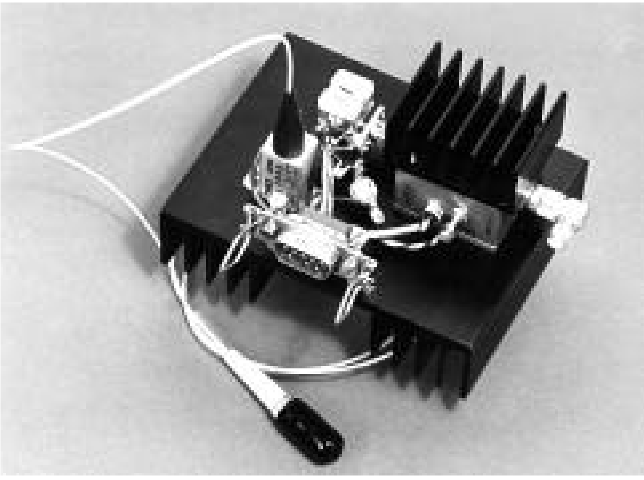

Fig. 2 Laser transmitter head module

Multimode Fabry-Perot lasers are less expensive and available with higher output powers than distributed-feedback types. They are considerably less sensitive to optical feedback noise and as a result have been found to perform satisfactorily without the use of isolators in spite of the Fresnel reflection from multiple inexpensive (non angle-polish) connector interfaces in the distribution path.

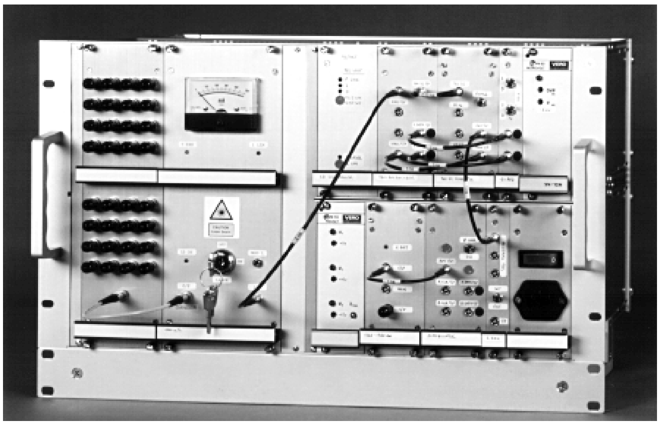

Fig. 3 TTC transmitter crate

At 1310 nm, even inexpensive LED sources having a relatively broad output spectrum can be used successfully for low-power test systems, whereas at 830 nm the fibre dispersion of 80 ps/nm.km (1 ns for a 125 nm wide source and 100 m length of fibre) excludes them from applications requiring precise timing. While somewhat higher laser powers are currently available from the most expensive short-wavelength AlGaAs lasers than from long-wavelength InGaAsP diodes, this gap is narrowing and the projected lifetime of the latter devices is more than an order of magnitude longer.

Step index multimode fibre is unsuitable for this application because of its large multimode dispersion, while the use of monomode fibre would incur high optical tree coupler and connector costs and limit the coupling efficiency from high power laser sources, which have divergent output beams. On the other hand, 50/125 μm graded index fibre can provide adequate bandwidth over the short path length (several GHz for 100 m) and is available in boron-fluorine doped form with good radiation tolerance characteristics.

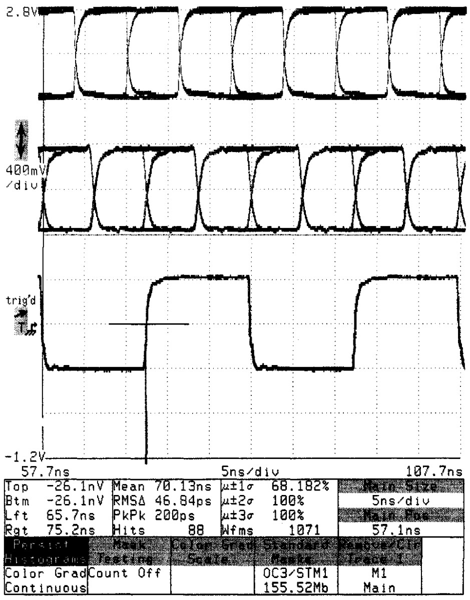

Fig. 4 *Upper trace*: 160.32 MBaud TDM encoder output
Centre trace: optoelectronic receiver output
Lower trace and histogram: recovered clock

Graded index fibre multimode dispersion varies with optical wavelength. Fibre that has low dispersion at 1310 nm is substantially cheaper than fibre that has the same dispersion at 830 nm or which has a compromise performance at both windows. Finally, both the appropriate photodetectors and the optical fibre itself are more radiation resistant at 1310 nm.

External modulators are normally polarization-dependent and have significant insertion loss. With direct modulation of currently available laser diodes it is quite feasible to broadcast reliably to groups of 1024 channels per transmitter through 100 m of 50/125 μm graded index fibre and two levels of 1:32 passive optical tree coupler. Fig. 2 shows the laser head module of the transmitter. It incorporates a 0.4 W RF amplifier with a bandwidth of 10 MHz - 1 GHz, an inexpensive bias tee fabricated with ferrite beads and an adjustable matching network for the very low impedance input of the laser diode. The laser has an integral Peltier cooler element and monitor thermistor, which permits a compact assembly. A complete transmitter subsystem crate is shown in Fig. 3.

This transmitter is capable of distributing the TTC signals through three levels of 1:32 tree coupler (1:32768 fanout). In practice more modest fanouts will be employed to allow adequate margins for component tolerances and radiation-induced receiver degradation. Fig. 4 indicates the performance when transmitting PRBS data at 160.32 MBaud with an optical fanout of 1:1024 and fibre length of 100 m.

The overall RMS jitter from the LHC clock input at the transmitter to the remote timing reference outputs, as measured by a wide bandwidth analyser without any filtering or smoothing, is in this case 47 ps. This is less than the spread in event origin time due to the LHC bunch collision length (180 ps RMS) and expected longitudinal phase modulation of the circulating beams.

IV. Encoding

As indicated in Fig. 5, the laser modulator is driven by an encoder which is phase-locked to the LHC clock and linked to an associated trigger select and serializer TTC-VME interface (TTCvi) module [4]. The TTCvi can also be programmed to generate pseudo trigger-accept sequences for test purposes.

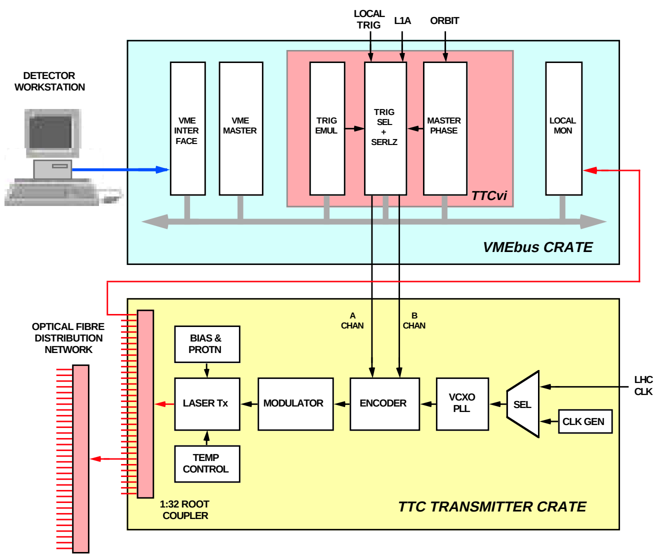

Fig. 5 TTC transmitter elements

The TTC system must deliver broadcast and individually-addressed signals to many thousands of front-end electronics controllers. An important reduction in receiver cost, power consumption, size and mass is achieved by encoding these signals in such a way that they can be received by a single optoelectronic detector per destination. The encoding should also allow the signals to be transmitted at a relatively low rate compatible with the photodetector/preamplifier devices that are being manufactured in the highest volumes and at the most competitive prices for the LAN market.

The code employed must be balanced (DC-free) so that the phase of the extracted timing reference is quite independent of the level-1 trigger data being transmitted. The signals must be reliably decoded by receivers that may be subject to radiation-induced sensitivity changes and offset shifts, so that the use of pulse amplitude modulation and non-binary transmission requiring multiple detection thresholds is excluded.

Evaluation of a number of signalling alternatives offering different tradeoffs between channel efficiency and synchronization precision led to the selection of a scheme whereby two data channels are time-division multiplexed (TDM) and encoded biphase mark at 160.32 MBaud (four times the LHC bunch-crossing rate) as shown in Fig. 6.

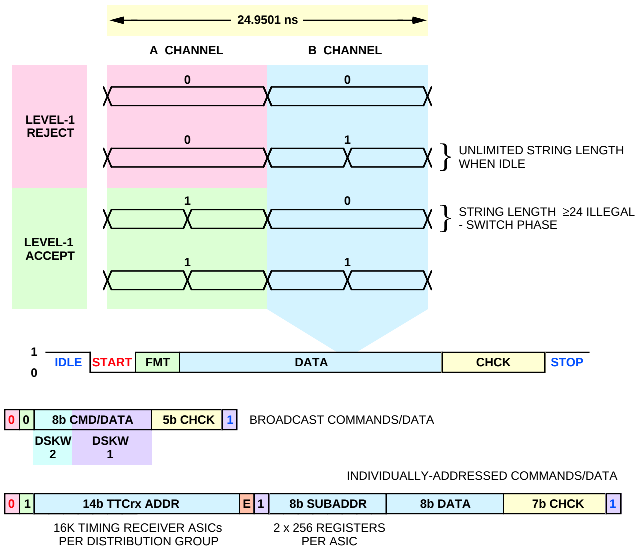

Fig. 6 TTC signal encoding

This is sufficiently close to the standard Sonet OC-3 (CCITT SDH STM-1) rate of 155.52 MBaud that an expanding range of photodetector/preamplifier components produced in increasingly high volume is appropriate.

The encoder 160.32 MHz VCXO is phase-locked to the LHC clock, or a local clock generator, by a PLL employing a high gain active loop filter with low offset drift. By means of an oscillator having low internal noise and a narrow loop bandwidth, a 160.32 MHz output jitter of less than 10 ps RMS can be maintained for a 40.08 MHz reference clock input jitter of several hundred ps.

The "prompt" TDM A Channel, which is designed for minimum latency, is dedicated to the broadcasting of the first-level trigger-accept signal, delivering a one-bit decision for every bunch crossing. The B Channel transmits broadcast and individually-addressed commands or data using the frame format shown in Fig. 6. The addressing scheme provides for up to 256 external and internal subaddresses associated with each of up to 16K timing receivers in each timing distribution group.

With standard two-channel biphase mark encoding, there is a fundamental ambiguity in the phase of the recovered clock. This is resolved automatically in the receivers by monitoring constraints on the data structure imposed by the B Channel data format. Hamming checkbits permit the forward error correction of all single-bit and the detection of all double-bit errors, as well as many others.

Since the B Channel is shared by a number of command and data sources, the TTCvi implements priority arbitration. During a short programmable interval at the end of the 3.17 μs LHC extraction kicker gap in one of the beams, other transmissions are held off so that the bunch counter reset signal can always be broadcast with exactly the required phase. Although this signal arrives at the receivers at different times because of the different lengths of the optical fibre paths, it experiences the same propagation delay to any receiver as the trigger-accept signals and so does not require separate delay compensation.

High priority is assigned to other synchronous broadcasts, while in the background the timing calibration controller continuously scans all the timing receivers transmitting fine deskew adjustments to compensate for phase wander due to changes of temperature, fibre tension, optical wavelength, signal amplitudes, voltage drifts and component ageing.

V. OPTOELECTRONIC RECEIVER

Although it is foreseen that LHC detectors will have many optical links for data readout and monitoring purposes, the TTC network may be one of the few systems requiring thousands of optoelectronic receivers located on and within certain subdetectors. The photodetectors used should have high optical signal responsivity, low sensitivity to ionizing and neutron irradiation and fast rise times at a low reverse bias voltage, preferably less than 3.5v.

InGaAs PIN diodes are superior to normal Si photodiodes in most technical characteristics including radiation hardness. The current packaging configuration approach for TTC optoelectronic receivers is a subminiature connectorized InGaAs PIN + Si bipolar preamplifier device with differential outputs connected directly to a separately packaged low-power CMOS timing receiver ASIC containing the postamplifier/AGC circuit followed by all the necessary analogue and digital functions. The PIN + preamplifier has shown little performance degradation after 4 Mrad ^{60}Co irradiation [5] and further tests are in progress.

Several manufacturers are currently introducing monolithic InGaAs/InP receivers in which PIN or MSM photodiodes are combined with a transimpedance amplifier using HBTs or MODFETs. Although clear performance advantages relative to hybrid designs have yet to be achieved, these OEICs could eventually open the way to the high volume fabrication of very cheap components, including “smart connectors” integrating all the standard optoelectronic receiver functions.

While conventional optical single-fibre connectors, such as the popular ST/PC type, are quite appropriate for use in small numbers at the TTC transmitters, they are much too massive for use at receivers in a particle physics detector and often contain high-permeability carbon steel springs and circlips. They are inconveniently large even for mounting on high-density modules in external electronics readout crates.

In collaboration with industrial partners, a new subminiature “RD12 Connector” is being developed for this application. The connector, which is non-magnetic and manufactured only from proven radiation-hard materials, mates with an active device mount designed to accommodate the PIN + preamp with an absolute minimum of additional mass and volume. Development prototypes have been manufactured (see Fig. 7) and pre-production testing is currently in progress.

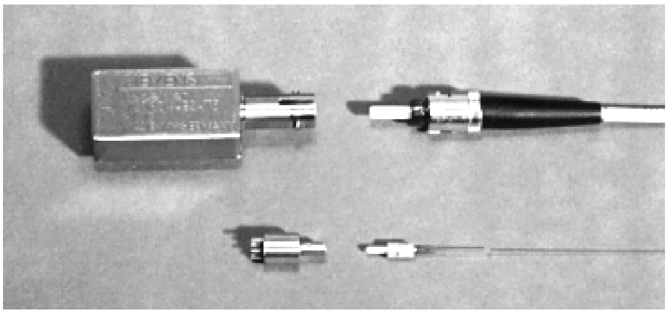

Fig. 7 Conventional ST and subminiature RD12 connectors

The RD12 Connector incorporates a zirconia ceramic ferrule to ensure high reliability, but its diameter is reduced to only 1.25 mm. ARCAP alloy is used for the device housing and polyether etherketone (PEEK), a glass-fibre enhanced thermoplastic material, for the connector shell. The PIN + preamp manufacturer actively aligns the TO-46 devices within the device mounts to ensure maximum responsivity, an operation that can be automated on a production line basis.

No really tiny affordable connector/device mount for single optical fibres has so far been brought to the commercial market. The RD12 Connector may meet this need in a number of future applications in other areas where very small size and low mass are important.

VI. TIMING RECEIVER

A timing receiver ASIC (TTCrx) for the TTC systems is currently being fabricated [6]. As indicated in Fig. 8, this VLSI chip accepts a single input from the TTC photodetector/preamplifier and generates a full range of decoded and deskewed signals for front-end electronics controllers.

The ASIC comprises an analogue part (including the postamplifier, automatic gain control circuits and clock recovery/fine deskew PLL) and a digital part (including the decoding, demultiplexing, coarse deskew, bunch counter, event counter and command processing sections). Any functions not required for a particular application can be disabled to minimise the TTCrx power consumption.

The TTCrx ASIC incorporates a multiphase clock generator and virtual programmable-length shift registers for fine and coarse signal deskewing respectively. These functions, as well as broadcast command generation and bunch and event counter resets, are controlled by the data transmitted over the B Channel.

It is assumed that the optical fibre path lengths in the TTC distribution system will be dictated by installation convenience alone and that their propagation delays will not be known precisely. Glass optical fibre is a rather elastic medium so that, even if the fibre lengths were initially cut with precision, significant changes would occur during installation and when opening and closing the detectors. However, records may be kept so that a data base of approximate delays is available for the initial setting of the deskews before beam is available to allow more precise tuning.

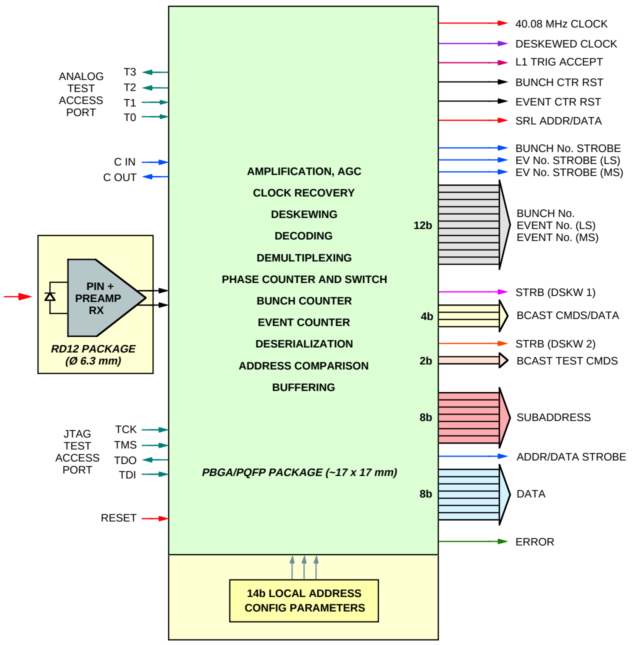

Fig. 8 TTCrx timing receiver ASIC

The bunch counter reset signal is also provided for external use but a 12-bit counter, which delivers a unique bunch crossing number synchronously with the corresponding first-level trigger decision, is integrated on-chip. All 3564 "potential" bunch crossings per orbit are numbered, since the actual LHC bunch structure can vary with the mode of operation, particularly during the initial commissioning and machine development phases.

During the 2 clock cycles following a trigger accept, for which the central trigger logic (global trigger) inhibits the generation of new triggers, the corresponding 24-bit event number is delivered on the same 12 output lines as the bunch number. Unlike the bunch counter, the event counter need not be reset periodically but rolls over after every 16M events (about every 3 minutes at the expected level-1 trigger rate of 100 kHz). All the TTCrx event counters are initialised by a broadcast command and may be reset by such a command during any gap in the LHC bunch structure.

The 12-bit bunch number generated by the TTCrx is required by the synchronisation algorithms and permits the study of correlations between event data and the LHC orbit. The 24-bit event number suffices to detect possible problems of event ordering or loss in the data readout and event building. Additional information, rendering the event identification unique, will of course be added to the data at later stages of the DAQ chain.

With suitable gating, the receiver clock-recovery function can be performed by a charge pump PLL with voltage-controlled delay elements. With this technology, which has already been used successfully by CERN for other applications [7], the fine deskew function can be implemented merely by the addition of a multiplexer since the loop inherently provides a full range of output phases over the bunch-crossing interval.

The bunch counter reset, and non-periodic signals such as the trigger decision and broadcast commands, will be deskewed by the timing receiver over a maximum 12-bit range; 4 bits for the number of bunch-crossing intervals and up to 8 bits for the phase within an interval. The coarse delay compensation range of 16 bunch-crossing intervals (total 399 ns) allows a substantial margin beyond the possible maximum variation due to differences in time-of-flight and optical fibre path length.

The broadcast command outputs have two independent coarse deskew registers for the number of bunch-crossing intervals. This is to allow some of them to be used for the generation of test and calibration signals having different delay compensations (excluding time-of-flight but including test signal latency, for example) without having to reload the deskew parameters used for normal running.

VII. Conclusion

The development of TTC systems for the next generation of collider experiments presents a number of challenges in the areas of high-power laser transmitters, encoders and modulators, passive optical couplers, VLSI microelectronics, synchronization management and low-cost sub-miniature optoelectronic receivers. These challenges are being tackled successfully in LHCC/LERB Project RD12 by a collaboration of CERN groups, associated research institutes and industrial partners. Further regularly-updated information is available on WWW at URL **http://www.cern.ch/TTC/intro.html**.

References

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